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Trace-Driven Simulation for LoRaWAN 868 MHz Propagation in an Urban Scenario

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Abstract—Long-range, low-power wide area network (LoRaWAN) is a very scalable solution for the Internet of Things (IoT). Performance evaluation of LoRaWAN in Urban environments is a challenging task. Theoretical modeling results have been inaccurate. In this paper, a trace-driven simulation for LoRaWAN 868 MHz propagation was performed using GPS data and their corresponding received signal level. The dataset has been extracted from 5015 datasets of LoRaWAN measurements taken from Glasgow city center. ICS-Telecom was used to simulate the real-world measurement environment. Comparison of trace-simulated results and the real-world data is performed to evaluate the prediction accuracy of Deygout 94, ITU-R 525/526 and COST-Walfish Ikegami (COST-WI) propagation models. All models over-estimated LoRaWAN trace-simulated received signal strength (RSS) levels in comparison to real-world collected samples. While Deygout 94 prediction accuracy was higher with *mean absolute error (MAE)* at 0.83 and *standard deviation (SD)* at 4.17, COST-WI performed poorly with *MAE* and *SD* at 2.87 and 10.96 respectively.

Keywords—LoRaWAN, Trace-Simulation, Deterministic models, Empirical Models, Received Signal Strength, ICS-Telecom, Urban Environment

I. INTRODUCTION

Propagation models are a tool for performance analysis of radio signals in research and industry. During the network planning process, models are used to fast-track radio coverage information. While deterministic models require terrain data to estimate the received signal strength accurately, empirical models do not. To effectively evaluate the performance of these models it is always good to validate the simulation results using field measurements data. Simulation models can give insightful information regarding the received signal strength falling within the receiver threshold as a network is rolled out. Some studies [1]–[4] have evaluated deterministic and empirical models' performance for various wireless technologies at different frequencies and environments. In literature, analysis of propagation performance models for low-power wide area networks (LPWANs) in urban areas has been presented. In Long-range wide area networks (LoRaWAN), for example, studies [5]–[7] have focused on the use of field measurements.

LoRaWAN [8] is a specification that defines the protocol and network architecture over which Long-range (LoRa)

technology operates. It is a low-power, long-range network connectivity for wireless sensor networks. Studies [9]–[11] show significant attenuation of LoRaWAN received signal strength in a non-line of sight (NLOS) environment.

In this paper, LoRaWAN trace-simulation results are generated and used to evaluate propagation models accuracy in ICS-Telecom for Glasgow city center. Accuracy of the propagation models is evaluated based on *mean absolute error, (MAE)* and *standard deviation, (SD)*. GPS coordinates and their corresponding LoRaWAN received signal levels were extracted from the real-world data measured from Glasgow city center. A dataset of 5015 elements was imported for simulation into ICS-Telecom. LoRaWAN trace-simulated results were generated and recorded along the waypoints for each propagation model on the city's map at 25 m resolution.

The main contributions of this paper are:

- A novel detailed LoRaWAN trace-driven simulation study of Glasgow city center is presented.
- Critical analysis of trace-driven results based on comparison and evaluation of standard propagation models with real-world measurements in Glasgow city center environment.

This paper is arranged follows: Section I briefly introduces Lora technology, LoRaWAN network, propagation models and the statement of motivation for performance analysis under this study. Section II provides details regarding the field measurements. Part III explains trace-simulated data. Section IV compares the models' performance analysis. Finally, section V presents the conclusion and prospective future work.

A. Overview of LoRaWAN

LoRaWAN is a low-power network technology that provides a Wide Area Network mobile or fixed applications and services for the IoT [12]. The specification V1.0 [13], for LoRaWAN published in early 2015, provides a detailed description of LoRaWAN network protocol and architecture of its network. It is a star-topology architecture that consists of the end-devices, the gateway, and the server. Figure 1. describes a typical star-topology of LoRaWAN network. While LoRaWAN defines system communication protocols and the architecture, LoRa, refined at the physical layer is used for modulation.

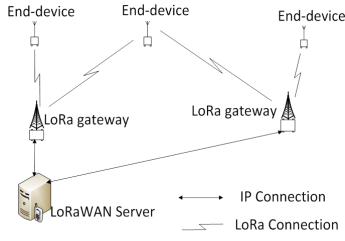


Fig. 1. Simplified LoRaWAN Network Architecture

Long Range (LoRa) [14] is a physical layer technology adapted by Semtech for digital wireless modulation in LoRaWAN networks. It uses chirp spread spectrum [15] to create long-range radio communication signals. This technique is key for LoRa to achieve a considerable communication range while retaining the ability to operate at low-power levels. A different spreading factor, SF is another key technology used in LoRaWAN network. It allows a trade-off between the coverage and data rates [16], with higher SF transmitting further for low data rate, and vice-versa.

B. Propagation Models

Propagation models [17] are used to predict the received signals strength in wireless networks. The propagation effects are heavily site-specific and dependent on the terrain, operating frequency, transmitter and receiver antenna height. These models can be deterministic, semi-empirical or empirical models and are used to estimate signal attenuation due to path, diffraction, multipath, etc., This study evaluates performance of Deygout 94, ITU-R 525/526 and COST-231 Walfish-Ikegami models for LoRaWAN propagation in Glasgow city center.

C. Deygout 94

Deygout 94 [18] model calculates attenuation due to diffraction and models obstacles as a knife-edge or round obstacle. It's concept is based on the main obstacle that exerts great obstruction loss between the transmitter and receiver. The overall attenuation is given as:

$$L_d = \sum_{n=i} L_d(V_i) \quad (1)$$

where L_d is the propagation loss if there is only one obstruction between the transmitter and receiver. If there are multiple diffracting obstacles, then the model calculates parameter V while ignoring other obstacles. It calculates the diffraction loss due to the first obstacle while ignoring other obstacles and considers this dominant edge as the terminal point of the two sections divided by two. The recursive process continues until it considers all the obstructions.

D. ITU-R 525/526

ITU-R 525/526 use the same concept as in Deygout 94 to calculate attenuation of the received signal strength due

to diffraction. For general terrestrial path, the model calculates diffraction geometry and subpath losses based on Delta Bullington. This model use free space loss, calculated in equation 4 as described in the ITU-R 525. The model has shown good performance [19] when used along with Deygout 94 for calculation of diffraction geometry. This analogy applies to our study.

E. COST-231 Walfish-Ikegami

Abbreviated as COST-WI [20], the model is a compound of Walfish and Ikegami models, and improves the path loss prediction through the consideration of more data to characterise large and medium-sized urban environments [21], that is, the buildings heights h_{Roof} , the widths of roads w , the separation between buildings b , and the angle θ with respect to the direct radio path. The range of fundamental parameters considered are between 800-2000 MHz for frequency, 0.02-5 km for distance, 1-3 m and 4-50 m for end-device and gateway antenna height respectively. The model makes a difference between the line-of-sight (LOS) and NLOS [22] and the mathematical formulae for both cases are defined in (6) and (7) below. If there exists a LOS in the street, the path loss is defined as:

$$P_{Loss} = 42.64 + 26\log_{10}(d) + 20\log_{10}(f) \quad (2)$$

In the case of NLOS, the path loss is the defined as a combination of path loss due to free space L_o , the rooftop to street diffraction and the scatter L_{rts} , and the multiple screen diffraction loss L_{msd} . This path loss totality is mathematically described as follows [21]:

$$P_{Loss} = L_o + L_{rts} + L_{msd} \quad (3)$$

where: L_o , the attenuation due to free space is given as:

$$P_{Loss} = 32.45 + 20\log_{10}(d) + 20\log_{10}(f) \quad (4)$$

L_{rts} , the diffraction loss from the rooftop to street is determined as in the following formula:

$$L_{rts} = -16.9 - 10\log_{10}(w) + 10\log_{10}(f) + 20\log_{10}(h_b - h_r) + L_{ori} \quad (5)$$

Here, w is width of the roads, h_b and h_m are the height of building and end-device mobile station respectively. The street orientation correction factor, L_{ori} [23] is given as:

$$L_{ori} = \begin{cases} -10 + 0.35\alpha & \text{for } 0^\circ < \alpha < 35^\circ \\ 2.5 + 0.0755(\alpha - 35) & \text{for } 35^\circ < \alpha < 55^\circ \\ 4 - 0.0114(\alpha - 55) & \text{for } 55^\circ < \alpha < 90^\circ \end{cases} \quad (6)$$

where α , is the street orientation angle. L_{msd} , the multi-screen loss, represent diffraction loss from multiple obstacles and it is determined by the following mathematical representation:

$$L_{msd} = L_{bsh} + K_a + K_d \log_{10}(d) + k_f \log(f) - 9\log_{10}(s_b) \quad (7)$$

where: the correction factors, L_{bsh} and k_a represent path loss when the gateway is above and below the rooftops respectively. The terms k_d and k_f quantify the diffraction loss as a factor of the distance and frequency, and are defined in [24] as follows:

$$L_{bsh} = \begin{cases} -181 \log(1 + h_t - h_b) & h_t > h_b \\ 0 & h_t \leq h_b \end{cases} \quad (8)$$

$$k_a = \begin{cases} 54 & h_t > h_b \\ 54 - 0.8(h_t - h_b) & h_t < h_b \text{ and } d_{km} \geq 0.5 \text{ km} \\ 54 - 1.6(h_t - h_b)d & d_{km} < 0.5 \text{ km} \end{cases} \quad (9)$$

$$k_d = \begin{cases} 18 & h_t > h_b \\ 18 - 15(h_t - h_b)/h_b & h_t \leq h_b \end{cases} \quad (10)$$

$$k_f = -4 + \begin{cases} 0.7(f_{MHz}/925 - 1) & \text{for medium-size city and suburban} \\ 1.5(f_{MHz}/925 - 1) & \text{for metropolitan centers} \end{cases} \quad (11)$$

F. Motivation for Performance Analysis

Considering the recency of LoRaWAN technology for the Internet of Things, some studies have evaluated the performance of LoRaWAN propagation in various urban scenarios. These studies are mainly based on the real-world measurements [5], [6], [25]–[27]. However, these works do not provide an alternative to individuals, private or public who may wish to plan for LoRaWAN networks. There is little work regarding the use of standard propagation models to assess the performance of LoRaWAN networks. In our previous work [28], the study of empirical propagation models for LoRaWAN in an urban scenario showed that COST-WI performed better received signal strength (RSS) estimations than other studied empirical models. However, its performance significantly over-predicted the received signal strength (RSS) indicator by 6.48, and this can mislead LoRaWAN network planning process.

In the presented work within this paper, GPS data, and the corresponding received signal levels measured in Glasgow city center are imported into ICS-Telecom without costly high-resolution terrain maps. The GPS data constitute the latitude, longitude, and along with their corresponding receive signal levels. The data was extracted from the real-world data measured in Glasgow city center, and models use it to generate LoRaWAN trace-results that are estimations of the RSS indicator. Comparison of traced-results with the real-world measurements facilitate the comprehension of performance accuracy and validity of deterministic, semi-empirical, and empirical propagation models when used for the radio coverage planning of LoRaWAN networks. This study can be used to give an insight into the effectiveness of standard propagation models for evaluation of IoT connectivity with LoRaWAN networks at 868 MHz in NLOS urban environment.

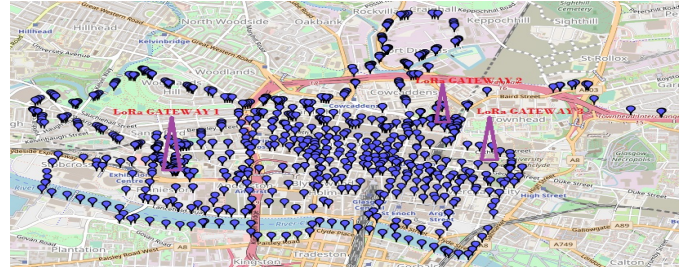


Fig. 2. A Google map showing LoRa Gateways and a LoRa end-device in Glasgow city center measurement locations

II. FIELD MEASUREMENTS

The real-world measurements were taken from Glasgow city center, the United Kingdom. The equipment used is LoRaWAN end-device with a Multitech mDot module, regulated by a Raspberry Pi single board computer and three gateways equipped with Lora SX1301 [29]. The gateways operated at spreading factors, SF7 - SF12 from three locations. 30 m on top of George More building, Glasgow Caledonian University, 27 m on top of Skypark and 27 m on top of James Weir building at Strathclyde University. The transmitting end-device was set to operate at 868 MHz frequency band and 14 dBm. It received and dropped the packets based on the Lora sensitivity. Figure 2. is the display of Glasgow city center topology from where the measurements process was conducted.

III. SIMULATIONS

The simulation was performed using the ICS-Telecom simulator, a commercial network planning tool with several propagation models. The simulator has LoRa and LoRaWAN protocol embedded in it. The ICS-Telecom trace-simulation requires the latitude, longitude, and RSS data. A dataset containing 5015 information regarding the latitude, longitude and RSS was imported into the ICS-Telecom through the measure function. This dataset was obtained through the manipulation of a 5015 dataset measured from Glasgow city center.

The simulation set up involved placing three gateways and one end-device over a 25 m resolution map of Glasgow city center. While the end-device was mobile, three static gateways were placed at Glasgow Caledonian University, University of Strathclyde and Skypark. Each gateway location settings on the map matched the latitude and longitude of real-world gateways used during the measurements. However,

TABLE I. SIMULATION PARAMETERS

Parameters	Values
Operating frequency Band	868 MHz
Bandwidth	125 kHz
End-device transmit power	14 dBm
Number of Gateway	3 m
Gateway antenna heights	30, 27 and 27 m
End-device antenna height	1.5 m
Spreading factor (SF)	12, 7 and 8
Maximum Distance between tx and rx	2275 m

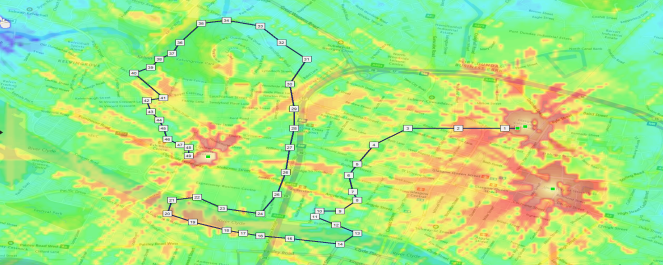


Fig. 3. Bing map showing simulation of LoRaWAN Network in Glasgow city Centre

low resolution terrain maps such the 25 m provides digital elevation model and the city's clutter to the simulator, leaving out the building layer. Figure 3 shows set up of the simulation.

Trace-simulated RSS recording followed the waypoints for each propagation model. The study recorded nearly 100 dataset for each model. The trace-simulated RSS were played and recorded at every location over the map as the cursor points to the area. During the simulation, the trace-simulated RSS levels either rose or dropped following the distance from the gateway. As seen in Figure 3, the color code shows signal strength, which depends on many factors, including used model, obstructions in the environment, interference, etc., Table I. shows some of the parameters used to configure the end-device and gateways.

IV. MODELS PERFORMANCE ANALYSIS AND VALIDATION

LoRaWAN received signal strength results for each of the three models are evaluated with respect to the real-world simulation data for which GPS coordinates and received signal levels are imported. The validity of LoRaWAN trace results for each model is determined based on the comparison with LoRaWAN 868 MHz measurements taken in Glasgow city center. The radio propagation environment considered for measurements and simulations is NLOS since there is no direct visibility between the LoRaWAN end-device and the three LoRaWAN gateways in the measured locations. Table 2. indicates the statistical error performance metrics calculated

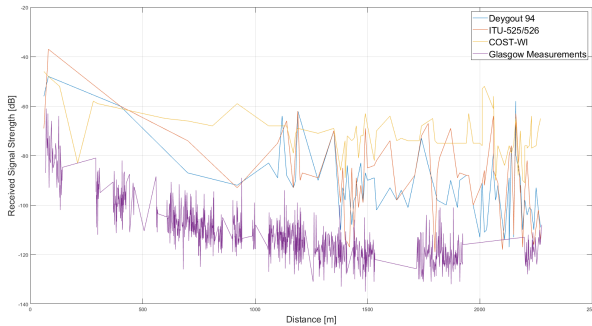


Fig. 4. Models Performance Comparison for LoRaWAN 868 MHz

TABLE II. MATHEMATICAL ERROR PERFORMANCE METRICS

Error parameters	Deygout 94	ITU-R 525/526	COST-WI
$ \Delta y $	0.83	1.01	2.87
σ_e	4.17	5.84	10.96

in equations 16 - 18 for the measured and models predicted values in the NLOS city environment.

The comparison between models' trace-simulation results and data measured in Glasgow city center for LoRaWAN 868 MHz in NLOS conditions is shown in Figure 4. It plots the received signal strength as a function of the distance, in meters and received signal strength, in dB. The clustered data observed is an indicator that many packets were collected in high-density areas of Glasgow city center whereas the straight lines show areas where signals were obstructed entirely due to high density and a considerable number of tall buildings.

The propagation models used in this work is evaluated for prediction accuracy using mathematical functions and the real-world data measured in Glasgow city center for benchmarking. While *mean absolute error (MAE)* is used to assess propagation models prediction accuracy, *standard deviation (SD)* measures the size of the predicted received signals deviation away from the average real-world measured data. However, [30] argues that it may be necessary to use both *MAE* and *root-mean-squared error (RMSE)* value to evaluate the average model's prediction accuracy. The terms used to represent error measuring parameters, *Mean Absolute Error*, $|\Delta y|$ and *Standard Deviation*, σ_e are presented. In this paper, Δ_{yi} denotes the difference between estimated and measured data, whereas N indicate the total number of data considered samples. These terms are used for performance analysis and are calculated in the formulae below. It was observed that all the three models over-estimated the received signal power strength. However, Deygout 94 registered higher accuracy with *MAE* at 0.83. The *MAE* for ITU-R 525/526 and COST-WI was 1.01 and 2.87 respectively. In addition, Deygout 94 exhibited the lowest *standard deviation*, $\sigma_e = 4.17$, followed by ITU-R 525/526 Deygout 94 and COST-WI at $\sigma_e = 5.84$ and $\sigma_e = 10.96$ respectively. This result implies that Deygout 94, a purely deterministic model, performs better than other models under this study. The COST-WI poor prediction performance may be attributed to its reliance on the buildings information that is absent in the model.

$$\Delta_{yi} = Power_{estimated} - Power_{measured} \quad (12)$$

$$|\Delta y| = \frac{1}{N} \sum_{i=1}^N |\Delta_{yi}| \quad (13)$$

$$\sigma_e = \sqrt{\frac{1}{N} \sum_{i=1}^N (\Delta_{yi} - |\Delta y|)^2} \quad (14)$$

V. CONCLUSION AND FUTURE WORK

Using trace-driven simulation we have analyzed several propagation models to find the best model for LoRaWAN in Urban environment. GPS data and received signal levels were extracted from 5015 datasets of LoRaWAN measurements taken from Glasgow city center. This dataset was used to perform LoRaWAN 868 MHz trace-driven simulation using ICS-Telecom. Trace-simulated results and the real-world data have been compared to evaluate the prediction accuracy of Deygout 94, ITU-R 525/526, and COST-WI. All models over-estimated LoRaWAN trace-simulated RSS levels in comparison to real-world collected samples. Deygout 94 prediction accuracy was the higher with *MAE* at 0.83 and *SD* at 4.17. COST-WI cannot be used for simulation of LoRaWAN coverage estimation in an urban environment unless there is a building layer in ICS-Telecom. To date, most studies use measurements to evaluate LoRaWAN performance. However, it's is expensive, and simulation is a better option. To accurately model the actual measurements, advanced machine learning is an option for future research work.

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